Spring 2005
Industry Study

Final Report
Strategic Materials

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National Defense University
Fort McNair, Washington, D.C. 20319-5062

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
2005	**N/A**	**-**

4. TITLE AND SUBTITLE	
Strategic Materials Spring 2005 Industry Study	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **The Industrial College of the Armed Forces National Defense University Fort McNair Washigton, DC 20319-5062**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**SAR**	**47**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

STRATEGIC MATERIALS 2005

ABSTRACT: Strategic materials are those materials and related technologies whose critical function or availability is essential for US economic competitiveness and security. Emerging materials and innovative technologies are key enablers to military transformation and economic growth. In order to retain its competitive advantage, the US must initiate a comprehensive National Materials Strategy to focus and revitalize the climate for innovation, to develop strategic partnerships for rapid commercialization, and to ensure the accessibility, availability, and affordability of critical materials. In summary, the US should again view materials as strategic given their role as a critical enabler for economic prosperity and security.

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INTRODUCTION:

Materials have always played a central role in the advancement of society and improvement in quality of life. Materials create wealth, improve our standard of living, and are crucial to meeting society's needs, from national security and communications to health and housing.[1] History itself uses materials breakthroughs as identifiers of significant societal advancements. The Stone Age, the Bronze Age, and the Iron Age descriptions have been used to identify progress usually associated with mastery of the materials in that age. Some have labeled today's period as the Silicon Age, but after 30 plus years of rapid advancement, we are nearing the fundamental limit of silicon-based technology.[2] However, the commensurate increases in computational power and advances in instrumentation have positioned us to take the next step. Materials science has undertaken recent movements away from the traditional "Edisonian" method of trial and error in materials discovery to a systems-based approach of materials designed to meet specific requirements. This transition indicates that the next great age may be the Materials Design Age.[3] Dr. Olson, a respected material scientist, describes this environment as follows:

> "The science of materials has reached a level at which it now can radically change engineering practice… Until the 19th Century, there was little or no science to guide medical technology and practice. Since then, however, the ever-growing corpus of biomedical knowledge has been leading to an ever more amazing stream of health care innovations… The materials research community is poised to emulate this model."[4]

The convergence of physics, chemistry, biology, and information technology, driven by the availability of tools to investigate, manipulate, and model the molecular structure of materials, will usher in this new age and lead to unimaginable advancements and changes to our way of life. The problem is that these materials do not just happen. They require investment in research and commercialization. The question is: Will the US lead this revolution or follow other nations? The economic benefits and the commensurate standard of living and quality of life are at stake. In order to position the US for continued leadership, the US must complete a critical review of the current strategic materials landscape and take appropriate action to address current and future challenges. Along those lines, the following sections will define the strategic materials industry, report on current conditions and emerging challenges, and propose US government roles and policies.

STRATEGIC MATERIALS INDUSTRY DEFINED:

Strategic Materials Defined. Webster's Dictionary defines material as "the elements, constituents, or substances of which something is composed or can be made."[5] A quick review of the period table reveals some 100-plus elements that would constitute material using Webster's definition. Factoring in the thousands of substances one can engineer from these basic building blocks makes a review of materials a near impossible task.

The US Department of Defense (DOD) defines a strategic material as "material required for essential uses in war emergency, the procurement of which in adequate quantity, quality, or time, is sufficiently uncertain, for any reason, to require prior provisions of the supply thereof."[6] DOD's definition is consistent with that of the US Congress, which defines strategic and critical materials as those materials that "would be needed to supply the military, industry, and essential civilian needs of the United States during a national emergency, and … are not found or produced in the United States in sufficient quantities to meet such need."[7] Strictly applied, these definitions would prevent consideration of those materials and technologies vital to the US economy.

With this later inadequacy in mind, the seminar settled on the following working definition: Strategic materials are those materials and technologies whose access, cost, properties, and functions are essential to the economic advantage and national security of the United States.

Strategic Materials Industry Scope. Because of the crosscutting nature of strategic materials, the industry is likewise complex and not easily broken out from other industrial sectors. The strategic materials industry consists literally of thousands of academic institutions, government agencies, extraction operations, manufacturers, suppliers, and system integrators. Therefore, the seminar subdivided the strategic materials industry into following three areas based on impact on the US economy as illustrated in Figure 1: foundational, current and emerging, and future materials.[8]

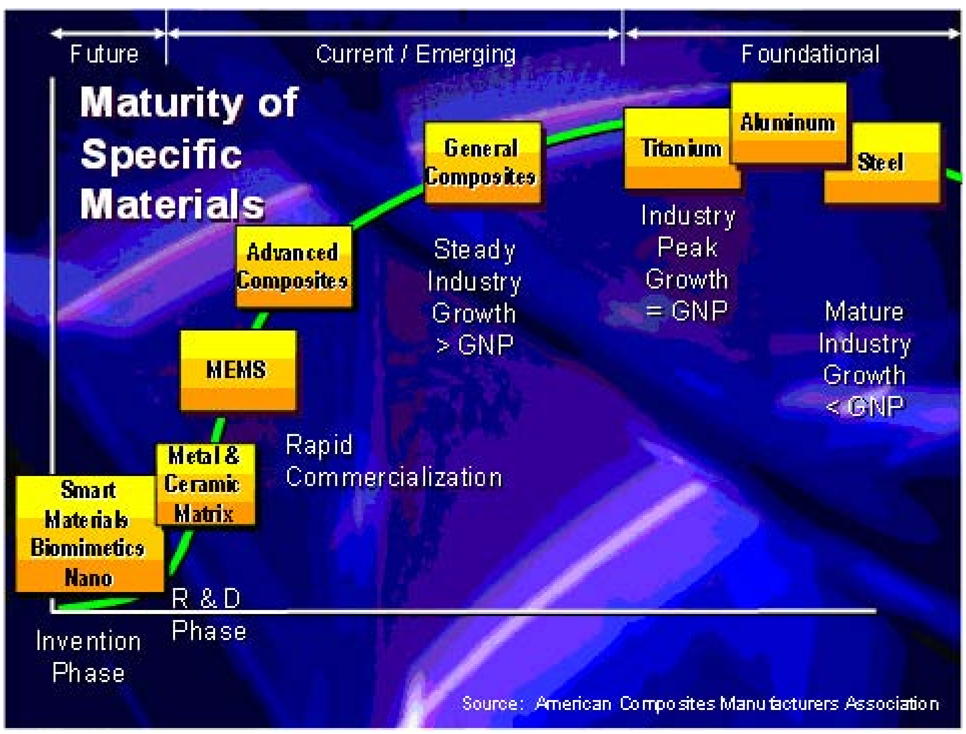


Figure 1. Maturity of Specific Materials and Technologies

The seminar classified foundational materials as those materials having a long and important relevance to commercial and defense sectors and national economy. Such materials include steel, aluminum, and titanium. The seminar further classified current

and emerging materials as those materials and technologies that have recently become integral to or are finding acceptance in commercial and defense sectors. Such materials and technologies include superalloys, advanced composites and ceramics, rare earths, MEMS, and powder metallurgy. Finally, the seminar classified future materials as those materials and technologies that have great potential, but require additional research and development before they will be in wide use. Such future materials include biomimetics and nanotechnology. Overall, the seminar considered only non-fuel materials and technologies and therefore excluded such vital materials as oil, coal, and uranium. The next section will briefly describe each of the aforementioned materials before addressing the challenges and outlook for the strategic materials industry.

CURRENT CONDITION OF THE STRATEGIC MATERIALS INDUSTRY:

Strategic Materials: Yesterday and Today. Along with air, water, and food, humanity's very existence depends on materials. Throughout its rich history, the US has benefited greatly from an abundant domestic source of or access to materials. Today, the US finds itself in a dominant position in the global economy due, in part, to its ability to rapidly access and transform materials into commercial and defense products. However, increased dependence on material imports, increased global competition for materials, declining R&D budget, rising energy costs, and an aging working force confront the US and its ability to maintain an economic advantage.

Throughout the post-World War II through Cold War era, the US played a key leadership role in materials science, which, in part, resulted in sustained prosperity and security for the US and its strategic partners. The linkages between leadership in materials science, prosperity, and security are not readily evident to the casual observer. However, the linkage becomes clearer when one considers how the US economy provides the means for our strong defense and its superpower status. In essence, "technology advances have accounted for between 50 and 70 percent of the improvement in our standard of living since World War II."[9] Peeling back one more layer, we find that "materials science underpins every product and process on which our modern society depends."[10] According to the National Materials Advisory Board,

> "Materials enabled most of the great engineering achievements of the twentieth century. Without materials improvements, seven of the top ten accomplishments would have been impossible: the Apollo moon landing, the airplane, the transistor, the Manhattan Project, the integrated circuit, the airplane jet engine, and the communications satellite. The other three -- digital computers, television, and the Panama Canal -- all benefited from better materials, too, even if they did not absolutely require them."[11]

Although determining an exact dollar value representing the overall contribution of materials to the US national economy is near impossible, materials do have a primary, secondary, and tertiary role in the 11 trillion dollar US economy.[12] From the raw ores, minerals, and materials extracted from the earth and oceans to the source materials that drive the manufacturing sector to the materials that support the transportation and information service industries, materials have been and will continue to serve a

foundational role in the US national economy. Therefore, failure to maintain US leadership in materials science and to commercialize successful advancements through domestic companies will invariably lead to a decline in our global economic status and a resulting decline in our national security.

Current Conditions Summary. In general, the materials environment is shaped by outside forces for improvement, survival, and leadership. These major outside forces include energy costs for manufacturing, national dependency on imported raw materials, decreasing market share of bulk products due to lower global labor rates and environmental standards, and increasing international competition for leadership in the materials of tomorrow. A discussion of each specific material along with a brief assessment of the relevant shaping forces is provided below.

Foundational Materials.

Steel. The US steel industry is thriving in the world market and has positioned itself to compete in the global marketplace by restructuring, consolidating operations, and becoming the world leader in production efficiency and energy savings. These initiatives along with investments in research and development have enabled the US steel industry to maintain competitiveness in the global market.

The future, though challenging, appears promising for the US domestic steel industry. The US ranked third behind China and Japan in global steel production for 2004. Most of the growth in the international market is due to China's rapid growth. China's production capacity has nearly doubled in the last five years. Consequently, the US must work closely with international partners and the World Trade Organization to limit the flooding of the global market with heavily subsidized steel from China and other countries who subsidize their production facilities. Since 1975, the US steel industry has invested more than sixty billion dollars in new technologies that have improved energy efficiency and productivity. In the last twenty-five years, annual energy consumption by the steel industry has been reduced by more than 17 percent.

The American steel industry has developed specialty steels and manufacturing processes to meet critical DOD requirements. Steel is used in just about every major military platform including aircraft carriers, tanks, aircraft, ships and gun barrels. Steel remains a critical material to US national security, so it is vital that the US steel industry maintain the capability to acquire the raw materials and scrap steel necessary to maintain industry productivity.

Aluminum. Aluminum is one of the few products and industries in America that truly affects every community in the country, either through physical plants and facilities, recycling, heavy industry, or consumption of goods. Aluminum is made in an electrometallurgical process from two sources: primary -- produced from ore -- and secondary -- recycled from metal scrap, also known as secondary recovery.[13] In the primary production method, bauxite ore is mined and refined into alumina (aluminum oxide) which, in turn, becomes the feedstock for aluminum metal. The secondary production methods draws from old or new metal scraps to produce aluminum metal (a less energy intensive process).

Aluminum alloys are designed and produced to achieve desirable characteristics, including strength, formability, and corrosion resistance. Some of the common elements alloyed with aluminum include copper, manganese, silicon, magnesium, and zinc and the list continues to broaden. Typical applications and uses of aluminum alloys include building products (siding and structural), rigid and flexible packaging (foil, food, and beverage cans), and transportation (automobiles, aircraft, ships and railcars). A comparison[14] of mechanical properties of aluminum powder metallurgy shows, that its major advantage is the density. Other significant property includes corrosion resistance, conductivity, and finishing characteristics. These properties will continue to allow aluminum and aluminum alloys to provide value for the commercial and defense sectors

Overall, the US aluminum industry's greatest challenge is in overcoming the high-energy demands required to produce primary aluminum. Recent increases in energy costs have caused the temporary closure of several US production facilities and the opening of offshore sites where energy is more accessible and affordable.

Titanium. As the ninth most abundant element in the earth's crust, and the fourth most abundant metallic element, titanium is strong, light weight, and versatile. Possessing the highest strength-to-weight ratio of any of today's structural metals, it is commonly used in aircraft, chemical and petrochemical processing, offshore oil and gas, marine, and desalination industries, and more well-known consumer applications such as golf clubs and medical implants. With its high strength-to-weight ratio and outstanding damage-tolerance properties, titanium is playing an ever-increasing role in the design of new, more mobile military systems. Australia is by far the largest supplier of both major mineral forms. The abundant titanium ores are widely dispersed rather than concentrated in large deposits. As a result, it is difficult and costly to produce in commercial quantities.

The largest single use of metallic titanium is in jet engines because of its strength, lightweight, and good resistance to fatigue. Titanium alloys are used in airframes and space structures such as solid rocket booster cases because of their lightweight and reliability. The percentage of titanium used in aircraft increases with each new design. The military's F-4 was nine percent titanium by weight, but the more modern F-15 is 26 percent and the future F-22 is projected to consist of 39 percent.

The extraction and processing costs to produce titanium ingot is about six times more expensive per pound than aluminum and 30 times that of steel.[15] Numerous initiatives are underway to reduce the cost of extracting, melting, and processing titanium, as well as attempts to utilize powder production technologies to manufacture complex titanium parts at significant cost savings. One promising new method known as the Cambridge process could make as much titanium in a day as traditional methods make in a week with resultant price drops up to one-third the current cost.[16]

The US military transformation effort requires weapon systems, and air, land, and sea platforms that are highly transportable, maneuverable, and survivable. Titanium provides the properties critically needed to achieve these transformation objectives.

Current and Emerging Materials and Technologies.

Superalloys. The term "superalloy" was first used shortly after World War II to describe a group of metal alloys developed for use in turbochargers and aircraft turbine engines that required high performance at elevated temperatures. Superalloys are strategically important because of their high temperature characteristics. The three major classifications of superalloys are nickel-, iron-, and cobalt-based alloys,[17] based on the dominant element in the alloy.

Superalloys provide distinct military and commercial advantages. Superalloys are required to meet the requirements of both high strength and operation at high temperature. A simple example of the military advantage of superalloys is an aircraft turbine engine that can operate at higher internal temperatures, producing higher thrust for a given weight -- a clear advantage.

The US leads the world in the production of superalloys, yet the health of the leading producers is poor -- and may remain poor for some time. America is increasingly dependent on imports to satisfy the demand and does not stockpile the crucial elements required for superalloy production. Competition with China for these elements will continue to drive prices higher, especially if nickel production does not increase.

Rare Earths. There are seventeen elements[18] referred to as "Rare Earths." Contrary to the inference, they are abundant in the earth's crust, but not concentrated in any place. Rare earth elements possess very diverse properties including nuclear, metallurgical, chemical, catalytic, electrical, magnetic, and optical, making them highly desirable for high-tech applications found in both the private and public sectors.[19] Unfortunately, extracting these elements from other materials is very expensive and time consuming (up to two years for some elements).[20] Even so, small amounts of these materials have become indispensable for electronic applications.

Defense applications include missile guidance systems, airplane cockpit displays, and phased array radar systems. Some rare earth elements are very useful for their magnetic and thermal properties and can be found at the leading edge of technology for miniature devices such as motors, ceramic devices, and power turbines.[21] However, the majority of the world's production (90 percent) is currently in China. The sole US extraction plant at Mountain Pass remains closed, but may resume operations in the near future.[22] Once on-line however, US dependence on Chinese imports will continue.

Research in the area of rare earths should continue with government sponsorship as they hold great promise in the solution to automobiles that are more efficient and faster, smaller, and higher performing electronics. The diversity of rare earth applications in private and defense sectors signifies their importance to US national security and economic growth.

Advanced Composites. Composites are materials created by combining two or more dissimilar materials to achieve a new material whose properties are superior to those of its constituents.[23] Composite materials are as diverse as laminated wood (plywood), porcelain enamel products (glass-coated metal), plastic- or metal-laminated corrugated paper, steel-reinforced concrete, fiberglass, and steel- or glass-reinforced rubber (tires). Composites are broadly known as reinforced plastics, and are typically composed of a reinforced fiber in a polymer matrix.

Composite materials and products affect virtually every current and future weapon system. They provide critical performance enhancements that enable the DOD to field superior weapon systems. Advanced composite structures offer vast potential to impact aircraft, missiles, space and satellite systems, land vehicles, ships, submarines, and multiple subsystems. These strong, lightweight structures improve range, speed, fuel efficiency, payload capability, and maneuverability. Since composite structures are generally resistant to fatigue and corrosion, they are known to greatly increase durability and mission readiness. Advanced composites will continue to dominate the aircraft and space industry.

Challenges facing the US composites industry are those that challenge industry at large: create the underlying climate of innovation to develop new materials, improve the manufacturing processes, broaden consumer markets, bridge the "valley of death" to bring new products to market, and shorten the time it takes to get a product idea to factory. Composites R&D must continue apace to ensure the development of versatile, lightweight, high-strength materials to support every major commercial sector -- especially energy/environment, transportation, construction, and security.

Advanced Ceramics. Advanced ceramics, distinguish themselves from ordinary pottery type materials, by their fabrication or combination with metallic elements to produce materials with better overall properties than just regular ceramics. The problem is that the cost of ceramic fibers and the low volume of production make these advanced ceramics very costly.

Advanced ceramics uses are in processing and manufacturing industries, power generation, aerospace, transportation, and military uses such as body armor. Defense shipments have decreased and the overall decrease in military-aerospace funding during the 1990's has reduced the opportunities for advanced processing and materials development in ceramics. Yet funding of advanced processing and materials development is needed to reduce the costs of advanced ceramics in order for them to compete with metals in a variety of applications.

Private enterprise, due to pressures for short-term returns on investment, cannot afford to invest heavily in improving ceramics production. Ceramics can be key to developing greater fuel efficiency and performance in engines, enhancing wear resistance of components, reducing weight of vehicles or aircraft, and reducing dependence on materials not available in the US (ceramics are usually based on common materials).

Powder Metallurgy. Powder metallurgy is a process that uses high pressure to convert powder metal into sophisticated component parts and assemblies, which could not otherwise be created with traditional methods. Powder metallurgy parts may be formed from iron, aluminum, copper, nickel, titanium, platinum, magnesium, strontium, rare earths, and other materials. The powder materials are not ground-chips or scraps of metals, but are metals reduced to powder by atomization of molten metal, reduction of oxides, electrolysis and chemical reduction. There are unlimited combinations of properties for powder metallurgy parts, which offer greater strength, improved density and many design options that would not be available in traditional metal processing.

Powder metallurgy parts are growing more strategically important to products in the automotive and aerospace industries. An aircraft engine may have more than 4,500

pounds of powder metallurgy superalloy parts. The properties of powder metallurgy components are crucial for aerospace applications because the parts function at high temperatures, while retaining tight tolerances.

The US powder metallurgy industry is made of both large and small firms, some private, while others are publicly held. This gives US firms greater flexibility to make investment decisions, while foreign firms are typically owned by larger parent organizations. However, the amount allocated to research and development is declining in the US with major private and public institutions unwilling to invest large amount of dollars into the field.

Micro-electro-mechanical System (MEMS). The integration of components into single micro-electro-mechanical systems (MEMS) have enabled the development of micro-sized mechanical components that can sense and measure multiple phenomenon. The integration of sensors with processors allows the realization of complete systems on a single chip. The sensors provide the eyes and arms while the processor provides the brains. Phenomena measured include mechanical, thermal, biological, chemical, optical, and magnetic activity. These systems allow the development of smart products greatly expanding the array of potential designs and applications.

The application of MEMS has steadily grown from its initial use as accelerometers in automobile air-bags. MEMS' small size and low cost are allowing designers to create many innovative applications. Because of the wide potential in military applications, the Defense Advanced Research Projects Agency's Research and Development Electronics Technology Office has funded numerous MEMS efforts. These include infrared, chemical and biological sensors.[24] In addition, the Naval Surface Warfare Center is working on multiple applications including safe fuzing and arming of weapons and in-flight guidance control.[25]

The key to maintaining the US edge on technology and manufacturing of MEMS lies in its ability to create the next application. With the rapid growth of applications for MEMS, the US should consider leading efforts to resolve the apparent lack of manufacturing standards and the unknown environmental impacts of MEMS devices. In addition, before pursuing more manufacturing of micro and nano scale devices, a scientific assessment of the impact on people and the environment should be conducted.

Future Strategic Materials.

Biomimetics. Biomimetic applications, based on an approach that leverages the methods and systems found in nature to produce material and engineering solutions to modern technological challenges, could benefit the US military through the implementation of basic and complex (smart) materials, complex structures, intelligent mechanisms, as well as innovative biomimetic material processes. Perhaps offering the greatest potential as a biomimetic material, spider silk "has the advantage of being both light and flexible, and pound for pound, roughly three times stronger than steel."[26]

Biomimetic initiatives could potentially benefit the US military and facilitate transformation into a leaner, more capable and adaptive force. Leveraging the methods and systems found in nature to produce material and engineering solutions capitalizes on the evolutionary pressures that have forced natural systems to become highly optimized

and efficient.[27] This approach will produce highly effective materials, structures, mechanisms, and material processes. However, due to the current US government R&D investment strategy, many of these initiatives will wither, unfunded.

Nanotechnology. Nanotechnology is the research and development of technology at the molecular and macro-molecular scale. Nano-engineering is not about making things smaller. Instead, nano-engineering manipulates materials at the near-molecular level to achieve dramatic, and sometimes surprising, advances in material characteristics. Nanotechnology has already found its way into vital DOD applications. The Navy is using nanotech paint on its submarines and surface ships to stop barnacle buildup and protect against corrosion. The Air Force is using the advancements in nanocomposites to make their unmanned aerial vehicles airframes radar resistant.[28]

The US government established the National Nanotechnology Initiative (NNI) as a federal government R&D program that provides long-term federal funding, leadership, and structure in the areas of nanoscale science, engineering, and technology.[29] With a billion dollar budget, the federal government is actively pursuing potential nanotechnology developments.

The US government has several leadership challenges with regard to the international community: (1) to determine what role it wants to have with the international community when it comes to sharing nano basic research, (2) to determine its role in helping to bring international nano basic research to the marketplace, and (3) to determine what kind of security collaboration it wants to utilize to ensure nano weapons do not get into the hands of unstable nation states and non-state actors. If nano engineering will affect almost every aspect of our lives then it makes sense that some nano products will change how the US will fight future wars. Nano weapons will be smaller and lighter, but with greater destructive capability.

Stockpiling Strategic Materials. Initially during World War I, and more so during World War II, the US diverted significant labor, equipment, and materials from the commercial to the defense sector in order to mobilize militarily for two global wars. These painful lessons pointed to the need for the US to acquire and maintain a stockpile of strategic and critical materials from which to draw upon during national emergencies. To this end, the US Congress enacted the Strategic and Critical Materials Stockpiling Act of 1946 and thereby created the National Stockpile, known today as the National Defense Stockpile. For roughly 45 years, the 1946 Stockpiling Act and key enactments of 1950, 1954, and 1979, served the US well and allowed it to persevere through the Korean, Vietnam, and Cold Wars.

The collapse of the Soviet Union in the late 1980s ushered in a new US war-planning construct that would dramatically reshape the National Defense Stockpile. Throughout the early 1990s, the stockpile objective declined as the world threat abated and the US reduced military force structure. In concert with this reduction, Congress approved through the Fiscal Year 1993 National Defense Authorization Act disposal of $3.7 billion in obsolete and excess materials. Since 1993, the National Defense Stockpile inventory has continued to recede. The National Defense Stockpile as of September 30, 2004 included 44 commodities valued at $1.56 billion. However, only three materials -- beryllium, quartz, and mica -- valued at $20 million are deemed necessary to meet

defense objectives. With congressional approval, the Defense National Stockpile Center classified the remaining $1.54 billion as obsolete and excess material.[30] At this current rate, the National Defense Stockpile for all practical purposes will cease to exist.

From a commercial standpoint, we found that stockpiling (e.g., warehousing extra material for a contingency) is no longer popular. Instead, industry has shifted to "just-in-time" supply and lean manufacturing practices. In some instances, companies have implemented long-term contracts with their strategic suppliers, including international sources, to limit supply disruptions and reduce price variability.

CHALLENGES:

Challenges facing the US materials industry are those that challenge industry at large: Creating the underlying climate of innovation to develop new materials; bridging the "valley of death" to transition new materials from the lab into the commercial domain; broadening consumer markets; accessing strategic materials; and reducing the cost of manufacturing. The following will highlight three of these important challenges.

Research and Development (R&D). R&D has long been considered the engine that drives innovation and economic development. Once the leader in R&D spending, the US is losing ground to near competitors. As Jeremy Rifkin points out in The European Dream, "The European Union leads the US in ... the number of science and engineering graduates; public research and development (R&D) expenditures; and new capital raised. Europe surpassed the United States in the mid-1990s as the largest producer of scientific literature."[31]

Between 1994 and 2002, US R&D spending grew at 6 percent per year.[32] This upward trend has ceased. US private industry, which traditionally contributed 60 percent to US R&D funding, has reduced its funding in order to trim costs; it is also funding short-term objectives at the expense of next-generation research.[33] Most private-industry R&D funding goes to development, with little going to basic and applied research.[34] Basic and applied research is needed for "knowledge creation" in order to understand scientific phenomena and solve the practical problems of innovation.

Federal R&D is dropping as well. The federal R&D budget for fiscal year (FY) 2006 is $132.3 billion, an increase of only 0.6% ($733 million) above FY 2005. This means the total federal R&D budget is declining, since this budgeted amount falls short of the 2 percent increase needed to keep pace with inflation. Most of this funding ($71 billion) is going toward defense R&D; health, space, and energy R&D will receive $28.7 billion, $16.5 billion, and $8.5 billion respectively. Funding for physical science, math, engineering, computer sciences, and environmental sciences is being cut. In addition, the basic and applied research budget comprises only 20 percent of the overall R&D budget and represents a 0.6 percent decrease compared with FY 2005.[35]

There are a number of reasons for insufficient US R&D investment. First, private industry has been cutting R&D in response to complex downturns in manufacturing and economic competitiveness, as well as rising healthcare costs for the labor force.[36] Second, federal R&D funding has been reduced. Third, a large portion of federal R&D funding is being diverted from non-defense R&D to defense R&D. Overall, it appears

that both government and industry are focused on short-term issues rather than long-term gains in national security and economic competitiveness.

Most economists believe that our R&D spending is responsible for our economic resilience and growing GDP. According to industry leaders, “The countries that create the best environment for innovation will be the economic powers for tomorrow.”[37] R&D is increasingly important, given the changes in global competitiveness and in global science and technology since the end of the Cold War. Because R&D investments by the private sector are decreasing, government must increase its role in stimulating innovation and expanding the education of our future scientist and engineers. R&D is particularly important to the materials industry because advances in materials lead to technology advances in most other fields.

The Valley of Death. In a National Materials Advisory Board report entitled *Materials in the New Millennium*, the problem in transitioning materials into the commercial sector -- the “valley of death” -- is a dual one:

> “The problem can be boiled down to two dilemmas. First, the market will not accept a new material until its cost falls, but its cost will not fall until the market accepts it. Second, designers will not select a new material until it is evaluated in service, but a new material cannot be evaluated in service until a designer selects it.”[38]

In order for the US to remain competitive, it is crucial that development and commercialization of innovative findings be fostered and that a sufficient base of scientists and engineers be educated to replace the aging baby-boom generation. Study after study has indicated that while the US retains leadership in research we do not fare as well in commercialization of those discoveries. If we do not improve at shepherding promising discoveries from design to manufacture or retain the educated technical workforce to pursue further advancements in materials science, our economy will be the victim of “creative destruction” on a global scale. Alan Greenspan described the process as follows:

> “Eminent Harvard professor Joseph Schumpeter many years ago called ‘creative destruction,’ the continuous process by which emerging technologies push out the old. Standards of living rise when incomes created by the productive facilities employing older, increasingly obsolescent, technologies are marshaled to finance the newly produced capital assets that embody cutting-edge technologies. This is the process by which wealth is created, incremental step by incremental step”[39]

Access to Materials. Throughout the post World War II and Cold War period, the US made considerable gains in implementing a stockpile program that enabled the US to endure modest mobilizations without suffering the sacrifices experienced during World War II. Although war-planning factors changed throughout this period -- from five to three to one and then back to three years -- the National Defense Stockpile enhanced US security, and at times the US economy, through an uncertain, bi-polar period.

The current US strategy remains defense focused, but not postured for today's reality. This reality includes a transnational threat to the US homeland, increased global competition for materials, and major new claimants on foreign material sources whose availability was previously instrumental to security. As further detailed in Appendix A, the US increasingly depends on foreign sources for non-fuel materials, including numerous strategic materials. The greatest challenge facing the US may be its ability to obtain strategic materials that are accessible, available, and affordable.

Of particular concern is the rising role of China as both a materials producer and consumer. A separate essay addresses this challenge in more detail.

STRATEGIC MATERIALS OUTLOOK:

Future trends, both commercial and defense, will continue to press for materials that enable lighter, stronger, multi-functional, longer life, lower life-cycle cost, and environmentally friendly solutions.[40] Such trends are driven, in part, by rising energy costs, global competitiveness, concern over degradation of the global environment, and national security transformation. In the short term, foundational materials will continue to play a vital role in the commercial and defense sectors, but will battle both internally and externally for market share. In the mid term, current and emerging materials will begin to dominate the commercial and defense sectors, with foundational materials taking a secondary role. In the mid to long term, maturation of biomimetics and nanotechnology coupled with advances in computational power and design tools will usher in the Materials Design Age.

Competition between Foundational, Current, and Emerging Materials. For foundational materials, this industry segment will continue to battle both internally and externally for market share. As a example of this internal battle, Jaguar Cars Ltd in 2003 as part of their XJ and XK series abandoned steel and instead shifted to an all-aluminum chassis and body, offering their customers improved driving performance, higher fuel economy, lower exhaust emissions, and lower cost of ownership. Advanced aluminum alloys and manufacturing techniques allowed Jaguar to overcome previous manufacturing and assembly impediments to include: (1) high-speed stamping of body panels, (2) fastening of aluminum parts, and (3) paint adhesion on aluminum surfaces.

This internal battle for market share is not limited to new products. As part of the Advanced Aluminum Aerostructures Initiative, the US Air Force and Alcoa have initiated a review of the existing C-17 and C-130 aircraft looking for opportunities to re-engineer critical components with advanced aluminum materials, component manufacturing, and assembly techniques. To date, the program has proved that an integrated approach that pairs a materials provider with a component designer can offer significant benefits.

Externally, Boeing's decision to increase dramatically advanced composites in the Boeing 787 design illustrates the move from foundational materials to current and emerging materials. As illustrated in Figure 2, the Boeing 787, in order to lower fuel consumption by 20 percent and lower overall lifecycle ownership costs, will incorporate 53 percent by weight advanced composites into the design.[41] If achieved, advanced composites will supplant aluminum as the predominant material by weight in the future

Boeing series of aircraft. Advances in composite properties and large-scale, automatic lay-up techniques allowed Boeing to make this strategic decision.

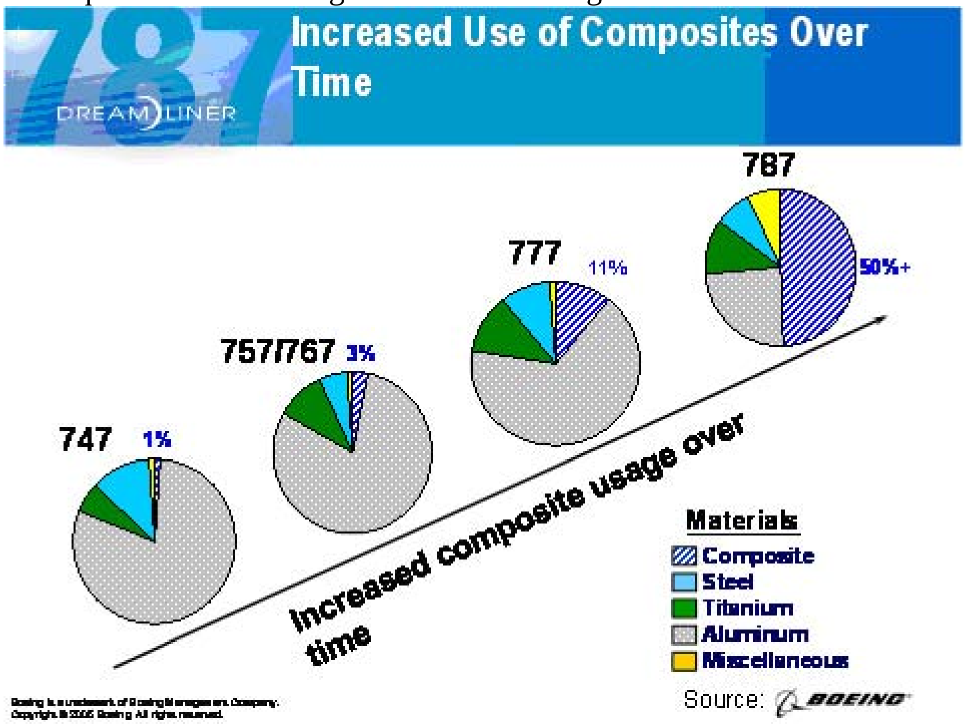


Figure 2. Increased Use of Composites in Boeing Commercial Aircraft

The Materials Design Age. The combination of significantly increased computational power along with the tools necessary for molecular investigation and modification will usher in the Materials Design Age. Material systems that leverage the design power inherent in nature's millions of years of evolution (biomimetics) will provide the foundation for advances in countless areas. Some examples range from camouflage clothing based on the principles used by octopuses to change colors and hide themselves to using infrared (IR) sensitive phosphorescent makers based on nature to identify friend from foe on the battlefield.

Nanotechnology is itself an evolutionary step in materials science. This evolution is a continuation of moving from the macro level to the micro level and now to the near-molecular level. Progress to date has shown the potential to engineer nano-materials with dramatically advanced properties and functions. While the advancement is evolutionary, the outcomes will be revolutionary, both for the commercial and defense sectors. The potential for significantly stronger, lighter, self-healing, and multifunctional materials is becoming better understood as illustrated in Figure 3, below.

This understanding is also at the heart of the increased worldwide investment in nanotechnology. Foreign nations are taking this race very seriously as can be seen in France with the creation of Minitec -- a government and industry funded research facility made available to the best minds that industry, government, and academia have to offer in the field. Another example can be seen in the partnerships created in the United Kingdom, through the London Centre for Nanotechnology, where they are focusing on a government, industry, and academia partnership to foster commercialization of initiatives that promise economic benefit and solve very real problems.

Source: US Army Research Laboratory

Figure 3. Vision of the Future Combat Soldier.

Ultimately, the race for leadership in the Materials Design Age will largely depend on the effectiveness of government, industry, and academia partnerships that successfully commercialize promising ideas.

GOVERNMENT AND INDUSTRY ROLES AND GOALS:

Government's Role and Recommendations. The US government's role lies in providing a national focus, fostering research, and advancing economic and national security. With respect to strategic materials, US leadership in this vital area has waned. In a recent National Academies report entitled *Retooling Manufacturing*, the role of government is, in part, spelled out concisely:

> "Bridging the gap between design and manufacturing may be too complex and costly for any lone firm to accomplish. The benefits of integration may be difficult to identify, much less quantify. Moreover, if the methods and technologies for bridging design and manufacturing are shared or intended to be made widely available in an open environment, firms may be unwilling to invest because they cannot benefit from these investments in the marketplace. The responsibility for the development and advocacy of such an approach comes to rest on a central entity, such as government"[42]

With this and previously addressed challenges and outlook in mind, the 2005 Strategic Materials seminar recommends the US government revitalize a National Materials Strategy -- one that provides a strengthened focus on research and development, rapid commercialization, and secure access to strategic materials.

A National Materials Strategy. The US should turn back the clock and revitalize a National Materials Strategy -- one that provides a renewed focus on materials science, research and development, and rapid commercialization. In the mid 1990's the US seemed to recognize the importance of materials to national security and a strong economy. In December 1995, the Office of the President issued a comprehensive report on the Federal Research and Development Program in Materials Science and Technology. At that time, one of the main priorities set by the National Science and Technology Council was materials R&D. The report's cover letter from the Assistant to the President for Science and Technology stated:

> "The Nation's economic prosperity and military security depend heavily on development and commercialization of advanced materials. Materials are a key facet of many technologies, providing the key ingredient for entire industries and tens of millions of jobs. With foreign competition in many areas of technology growing, improvements in materials and associated processes are needed now more than ever, both to create the new products and jobs of the future and to ensure that US industry and military forces can compete and win in the international arena."

This report on Materials R&D was the direct result of the first *National Security Science and Technology Strategy* -- a key supporting plan for the National Security Strategy. It recognized that our nation's security rests on three pillars: the readiness and capabilities of our military forces, our engagement with other nations to prevent conflict from occurring, and the strength of our economy.[43] Unfortunately, this was the first and the last *National Security Science and Technology Strategy*. The lost momentum in value of strategic materials became evident when a when a follow-on report was completed, but not released in 1999.

Unfortunately, this declining perception of the strategic value of materials and materials science continues in the President's Fiscal Year 2006 budget proposal. The budget reduces defense science and technology funding by 21 percent and cuts the Department of the Interior by 515 million dollars, essentially eliminating the US Geological Survey's mineral resources and water resources R&D programs. These cuts seem in direct contradiction to the National Security Strategy goal of "taking full advantage of science and technology." The US government must reverse this trend and move forward with a National Materials Strategy that focuses on the below areas.

A Renewed Commitment to Basic Research. Faced with the specter of increasing entitlements and interest payments on the national debt, America's near-term fiscal position remains challenging. Both of these issues have increased the pressure to reduce discretionary spending, to include Basic Research and Science and Technology funding, as evidenced by the President's FY 2006 budget. This action is short sighted

and we believe current and future reductions will increase the risk of the US falling behind economically in the long term.

We propose a tougher decision, but one we believe has the best chance of maintaining our leadership, prosperity and security. Approximately 50 percent of the discretionary budget goes for defense. With respect to R&D, defense is by far the largest recipient. However, DOD expends the majority of defense R&D funding on the development of new weapon systems, with lesser amounts, in recent years, going towards advances with broad commercial potential. On the other hand, basic research within DOD has historically provided many advances with commercial potential, especially in the areas of advanced materials and manufacturing. It is time to leverage our current military capability gap by eliminating development of some late term weapon systems in order to increase funding for basic research and commercialization initiatives. Although not intuitive, such a change would make US defense more affordable through the creation of more effective (both from a technical and cost standpoint) materials and manufacturing processes that underpin defense transformation while positioning the nation well for economic competition in the Materials Design Age.

In this vein, we also recommend a portion of available research funding go towards improving computational tools that advance and draw upon progress made in materials science and research. A materials knowledge base on the scale of the human genome project would set the foundation that couples materials, manufacturing processes, and component design. The creation of a comprehensive materials knowledge base linked with advanced design, manufacturing, and lifecycle management tools will reduce development time and cost, and position the US at the leading edge of the Materials Design Age.

Filling in the Valley of Death through Commitment and Excellence. The dilemmas above describe the "valley of death" that new materials face. How do you get the promising material out of the laboratory and into the factory? There are two broad areas where the US government can play a bigger role: (1) strengthening long term commitments with academia and small businesses and (2) rationalizing Centers of Excellence (COE) and consortia where the best from academia, industry, and government can come together to form "Strategic Triad" partnerships.

To remain competitive, large and medium-sized businesses, especially those supporting the defense sector, have become less vertically integrated and in the process reduced, if not shed, their basic and applied research activities. As a result, universities and small businesses have become the engine of innovation in the US. Unfortunately, these entities have difficulty in competing for the investment capital necessary to bridge the "valley of death." The US government has recognized this shift and instituted two programs -- the Small Business Innovative Research (SBIR) program and Advanced Technology Program (ATP) -- to kick-start the transition.

The current SBIR program seeks to leverage small business as a catalyst for developing break-through technology and novel products. It stimulates technological innovation by requiring federal agencies to set aside funding for relevant small business R&D. Currently, SBIR funding is limited to 2.5 percent of an agency's R&D budget. Further, the funding is given only for the start-up and proto-typing phases, but does not fund the commercialization phase of the SBIR three-phase program. In order to bring a

product from lab to marketplace, the small business must instead rely on venture capitalists, "Angels," larger firms or other non-SBIR government programs. As a result, only 39 percent of SBIR products successfully commercialize[44] due in large part to investor reluctance to invest in high-risk technologies. The valley of death results, in part, by the early cut-off of federal funding. We recommend increasing the SBIR set-aside to further stimulate small business, extend the period of funding into the critical commercialization phase, and re-establish the ATP currently zero-funded in the FY 2006 President's budget.

Second, we saw the use of Centers of Excellence (COE) and consortia as successful means to achieve "Strategic Triad" partnerships to transition technology. COEs support high technology ventures through a collaborative, multi-disciplinary approach among government, academia, private venture capital companies, and other private and public sector parties. Established to encourage rapid commercialization of scientific breakthroughs, COEs help fully leverage the practical, solution-directed collaboration needed to address the complex problems confronted by government today. COEs foster the exchange of leading-edge technologies, and sharing of best and "next" practices among government, industry, and academia. Such collaboration not only leads to advances in knowledge, but also fosters the relationships critical to transitioning the results of basic and applied research to the market place. The University of Delaware's Center for Composite Materials (UD-CCM) is a real-world example of the Strategic Triad model in action. UD-CCM employs a well-established consortium to transition research accomplishments directly to industry. Since 1978, UD-CCM has collaborated with 160 companies representing materials suppliers and end users in the aerospace, automotive, and durable goods industries. As the UD-CCM model shows, collaboration among "Strategic Triad" partners has proven fruitful in bridging the valley of death.

Many nations have recognized the need for a centralized and prioritized government effort to target promising technologies. While the US market model may have sufficed in the past to keep its competitive lead, the US need only look at how much this lead has shrunk to see the risks of continuing solely along this path.

Protecting Access: Time for a National Strategic Materials Stockpile. The 21st Century has ushered in an era filled with new global challenges and threats. Unfortunately, the US stockpiling policy is still set in an outdated estimating framework -- a framework that has yet to recognize emerging threats to the US homeland and the rise of economic peer competitors. The US must move forward with a revitalized strategy that will position the US to compete militarily and economically in a global, transnational environment.

The time has come for the US to reassess its stockpiling policy and move forward with a broadly focused policy, which factors in:

(1) The current defense war-planning construct, to include homeland defense and security objectives,

(2) The rise of economic peer competitors who not only have increased consumption requirements, but may also control production and price of critical materials,

(3) The defense transformation, specifically the need to stockpile new strategic and critical materials (i.e., rare earths, advanced composite constituents, superalloy base and alloying materials), and

(4) The need for an economic stockpile to assure accessibility, availability, and affordability of critical materials essential to the national economy.

ESSAY ON MAJOR ISSUES:

Rising China.

> "Yet if the people's Republic of China suffers from certain chronic hardships, its present leadership seems to be evolving a grand strategy … more coherent and forward looking than that which prevails in Moscow, Washington … And while the material constraints upon China are great, they are being ameliorated by an economic expansion which … promises to transform the country …"[45]

If China's objective is to become the world's most powerful nation, then military supremacy need not be in China's plans (yet) as they are well on their way to achieving the goal through another instrument of national power -- the Economic instrument. Looking back through history, one can appropriately compare today's China to the US in the late 19th Century. During that period, Britain was the world's superpower with many of the same characteristics as the US today. At that time, Britain maintained the highest GDP, the strongest military, and numerous global interests.

Perhaps the best measure of a nation's industrialization is its energy consumption, since it is an indication both of the country's technical capacity to exploit inanimate forms of energy and its economic pulse rate.[46] In 1850, the US was far behind Britain in energy consumption but by 1890, the consumption was about even. From that point on, the US energy consumption surpassed and then dwarfed Britain's providing an early indicator of the forthcoming US rise to superpower. Fast forward to the late 1990's and one finds China far behind the US in energy consumption. By 2020 however, US energy consumption is predicted to increase by 31 percent while China's is predicted to increase by 163 percent. Within 20 years, China's energy consumption will go from approximately 25 percent of the energy consumed by the US to 66 percent. China is catching up and fast.

Shifting to a comparison of gross domestic product (GDP), the Autumn 2004 Oxford Economic Forecast, "World Long-Term Economic Prospects" predicts China's GDP growing by an annual average of 7.67 percent, compared to 3.29 percent for the US. Comparisons between Britain and the US in the late 1800's to the US and China of today seem frighteningly similar. China is rising on a path similar to that which the US took to surpass Britain over 100 years ago. In fact, a RAND study cited in the Wall Street Journal predicted that "by the year 2015, the economies of the US and China will be running neck and neck -- with projected gross domestic product between $11 trillion and $12 trillion each."[47] Therefore, even using conservative forecasts, China is on track to overtake the US as the world's largest economy by 2025 at the latest.

From a strategic materials standpoint, China's growth has both US and global implications. As of 2003, China ranks number one in the production of aluminum, steel

(crude), rare earths, magnesium, antimony, lead, tin, tungsten, zinc, coal, and cement.[48] As China's industrialization continues, trends indicate that China's domestic consumption, especially in aluminum, iron ore, and steel, will outpace domestic production. In essence, China will become a net importer of foundational materials and the competition for these materials worldwide will increase. Such signs are already present as evidenced by rising materials prices, market volatility, and lower metals exports (rare earths, tin, and tungsten). As China's national economy matures and per capita income increases, China's demand for current and emerging materials will likewise grow and further compete with US market demands.[49]

Of particular concern is China's long-term vision and willingness to defer military expansion. As Kennedy states: "Perhaps the most remarkable aspect of China's 'dash for growth' has been the very firm control upon defense spending, so that the armed forces do not consume resources needed elsewhere. In Deng's view, defense has to remain the fourth of China's much vaunted "four modernizations" -- behind agriculture, industry, and science."[50]

The timing of all these factors does not bode well for the US. China has become a major player in the materials world, both as a supplier and consumer. The US must take proactive action now in light of China's continued focus on growing a science and engineering workforce and a strong position in raw materials sources. Such action should include a reassessment of the National Defense Stockpile and the need for an overarching National Stockpile Strategy encompassing national economic and security objectives and vulnerabilities.

Michael J. Boland, Dept of the Navy and Lt Col Kenneth L. Echternacht, Jr., USAF

CONCLUSIONS:

Materials have been and will continue to be the enabling technology that drives technological advances. Foundational (steel, aluminum, titanium), current (superalloys, rare earths, advanced composites), and emerging (MEMS, advanced ceramics, and powder metallurgy) materials will continue to underpin US economic prosperity and national security for the near future. However, the US dominant position in many of the strategic materials and technologies continues to wane as the US struggles through numerous challenges that affect its global comparative and innovative advantage. Current challenges affecting the US position in these strategic materials include higher energy costs, higher labor costs, increased global competition for materials, lower R&D efforts (both in the commercial and defense sectors), and an aging technical workforce.

In the mid- to far-term, we are entering a new Materials Design Age, where maintaining our leadership is vital to our national prosperity and security. Research budgets have been flat, at best, for the last 15 years and have contributed to a narrowing gap in technological competence. As a result, other nations are catching up. A serious bipartisan look at how we position ourselves as a nation for the future is overdue. As part of this review, the US must put forward a National Materials Strategy -- one that provides a strengthened focus on research and development, rapid commercialization, and access to strategic materials.

The nation is already facing a troubling fiscal outlook for the future with increasing mandatory expenditures and interest payments on the debt squeezing discretionary spending. The answer is not to cut basic research funding, but rather to rebalance the R&D portfolio. It is time to leverage our military capability gap and redirect funding from new weapon systems development into basic research and commercialization initiatives. A major step towards establishing long-term leadership in the Materials Design Age would be to establish a comprehensive materials knowledge base on the scale of the human genome project.

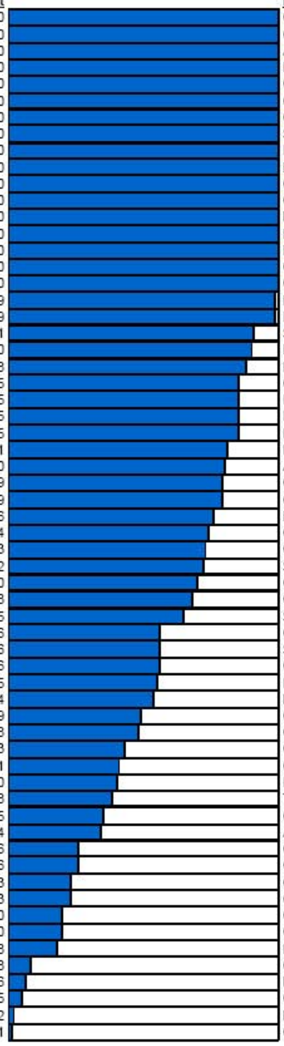
The US must also strengthen its market-driven approach to commercializing new materials and technologies. The US should further orchestrate strategic partnerships with academia and industry to rapidly transition future materials and technologies from the lab to the manufacturing floor. Such partnerships will foster commercialization of initiatives that support economic advances and solve very real problems … defense transformation.

The 21st century has ushered in an era filled with new global challenges and threats. Unfortunately, the US stockpiling strategy is still set in an outdated estimating framework -- a framework that has yet to recognize emerging threats to the US homeland and the rise of economic peer competitors. The US must move forward with a revitalized stockpiling strategy to ensure accessibility, availability, and affordability of strategic materials for both national economic and defense purposes.

In summary, it is time to again view materials as strategic and understand their role as a critical enabler for national prosperity and security.

Appendix A.

2004 U.S. NET IMPORT RELIANCE FOR SELECTED NONFUEL MINERAL MATERIALS



Commodity	Percent	Major Import Sources (2000-03)[1]
ARSENIC (trioxide)	100	China, Chile, Morocco, Mexico
ASBESTOS	100	Canada
BAUXITE and ALUMINA	100	Australia, Jamaica, Guinea, Suriname
COLUMBIUM (niobium)	100	Brazil, Canada, Estonia, Germany
FLUORSPAR	100	China, South Africa, Mexico
GRAPHITE (natural)	100	China, Mexico, Canada, Brazil
INDIUM	100	China, Canada, Japan, France
MANGANESE	100	South Africa, Gabon, Australia, France
MICA, sheet (natural)	100	India, Belgium, China, Germany
QUARTZ CRYSTAL (industrial)	100	Brazil, Germany, Madagascar
RARE EARTHS	100	China, France, Japan, Estonia
RUBIDIUM	100	Canada
STRONTIUM	100	Mexico, Germany
THALLIUM	100	Belgium, France, Russia, United Kingdom
THORIUM	100	France
VANADIUM	100	Czech Republic, South Africa, Canada, China
YTTRIUM	100	China, Japan, Austria, Netherlands
GALLIUM	99	France, China, Russia, Kazakhstan
GEMSTONES	99	Israel, India, Belgium
PLATINUM	91	South Africa, United Kingdom, Germany, Canada, Russia
BISMUTH	90	Belgium, Mexico, China, United Kingdom
TIN	88	Peru, China, Bolivia, Brazil
ANTIMONY	85	China, Mexico, South Africa, Belgium
DIAMOND (natural industrial stone)	85	Ireland, Switzerland, United Kingdom, Russia
STONE (dimension)	85	Italy, Canada, India, Spain
TITANIUM (sponge)	85	Kazakhstan, Japan, Russia
PALLADIUM	81	Russia, South Africa, United Kingdom, Belgium, Germany
TANTALUM	80	Australia, Kazakhstan, Canada, China
BARITE	79	China, India
RHENIUM	79	Chile, Kazakhstan, Mexico
COBALT	76	Finland, Norway, Russia, Canada
IODINE	74	Chile, Japan, Russia
TUNGSTEN	73	China, Canada
CHROMIUM	72	South Africa, Kazakhstan, Zimbabwe, Russia
POTASH	70	Canada, Belarus, Russia, Germany
MAGNESIUM METAL	68	Canada, Russia, China, Israel
TITANIUM MINERAL CONCENTRATES	65	South Africa, Australia, Canada, Ukraine
PEAT	56	Canada
SILICON	56	South Africa, Norway, Brazil, Russia
ZINC	56	Canada, Mexico, Peru
BERYLLIUM	55	Kazakhstan, Japan, Brazil, Spain
SILVER	54	Mexico, Canada, United Kingdom, Peru
NICKEL	49	Canada, Russia, Norway, Australia
MAGNESIUM COMPOUNDS	48	China, Australia, Canada, Austria
COPPER	43	Canada, Chile, Peru, Mexico
ALUMINUM	41	Canada, Russia, Venezuela, Mexico
DIAMOND (dust, grit and powder)	40	Ireland, China, Ukraine
NITROGEN (fixed), AMMONIA	38	Trinidad and Tobago, Canada, Russia
MICA, scrap and flake (natural)	35	Canada, India, China, Finland
GARNET (industrial)	34	Australia, India, China
GYPSUM	26	Canada, Mexico, Spain
PUMICE	26	Greece, Italy, Turkey
CEMENT	23	Canada, Thailand, China, Venezuela
PERLITE	23	Greece
SALT	20	Canada, Chile, Mexico, The Bahamas
SULFUR	20	Canada, Mexico, Venezuela
IRON and STEEL	18	European Union, Canada, Mexico, Republic of Korea
IRON ORE	8	Canada, Brazil, Australia, Chile
PHOSPHATE ROCK	6	Morocco
IRON and STEEL SLAG	5	Canada, France, Italy, Japan
FELDSPAR	2	Mexico, Turkey
TALC	1	China, Canada, France, Japan

[1]In descending order of import share

Source: US Geological Survey

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